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SECOND INTERIM SCIENTIFIC REPORT
DESIGN CRITERIA MONOGRAPH FOR
SPACE VEHICLE SOLAR CELL ARRAYS

by
Robert G. Lyle

June 1970

Prepared under Contract NAS 12-2237

by
EXOTECH SYSTEMS, INC.
Washington, D. C.

For
National Aeronautics and Space Administration
Headquarters

CONTENTS

1. INTRODUCTION AND SUMMARY
2. MEETING OF THE AD HOC ADVISORY PANEL
3. REVISION OF CONTENT DEVELOPMENT BOARDS
4. SCHEDULE FOR FIRST DRAFT MONOGRAPH
AND SECOND MEETING OF PANEL

/ APPENDIX A: Summary of First Panel Meeting

APPENDIX B: CDB's for First Draft Monograph

1. INTRODUCTION AND SUMMARY

This report covers the work accomplished under Tasks 3 and 4 of the Statement of Work in contract NAS 12-2237 for the preparation of a Design Criteria Monograph on Space Vehicle Solar Cells. The first of these tasks involved a meeting of the ad hoc Advisory Panel to review, critique, and add development to, the ERC SVDCO-Approved Content Development Boards (CDB's) which constitute an outline for the monograph. Task 4 involved revising and expanding the CDBs to reflect the recommendations of the Advisory Panel and the scope and content of the First Draft Monograph.

All of the requirements of Tasks 3 and 4 have been met and, upon approval of the results, the First Draft Monograph will be completed for distribution to the Advisory Panel before the next meeting in August.

2. MEETING OF THE ADVISORY PANEL

The ad hoc Advisory Panel for this monograph effort had its first meeting on Monday and Tuesday, May 25 - 26, 1970 at Washington, D. C. The purpose of the meeting was to review and critique the scope and content of a proposed outline for a monograph developed by Exotech, and develop recommendations concerning literature references and other information sources which should be used in the preparation of the monograph.

The panel members agreed that the central theme of the monograph should be the arrays of solar cells for spacecraft applications. Emphasis should be directed to the capabilities and limitations of silicon solar cell arrays, with detailed coverage of the following:

- . Energy conversion mechanism and efficiency
- . Methods for optimizing electrical characteristics

- . Alternatives of mechanical and electrical configuration design and their effects on overall performance of a solar cell power system
- . Environmental factors which affect performance and reliability of solar cells, and the concepts and techniques of design, fabrication, evaluation and testing which deal with environmental effects.

A summary of the minutes of the panel meeting is presented in Appendix A to this report.

3. REVISION OF CDBs

The presentation made to the Advisory Panel by Exotech staff was based upon the Content Development Boards (CDBs) submitted with the first Interim Scientific Report (May 1970) and approved by ERC SVDCO. The recommendations of the panel did not require extensive revision of format, scope or content reflected in the CDBs but rather provided significant added detail and identification of information sources which should be pursued.

An updated set of CDBs based on the results of the panel meeting is presented in Appendix B of this report.

4. SCHEDULE FOR TASKS 5 THROUGH 8

In the absence of any major changes of format, scope and content required as a result of the first panel meeting, the First Draft Monograph is now in preparation. The approach in this work is to keep the developing draft in a flexible form so that responses to this report can be accommodated readily and, at the same time, progress will be appropriate for

meeting the proposed schedule of August 7, 1970 for the next Advisory Panel Session. The proposed schedule for the meeting requires that the First Draft Monograph be distributed to the panel members by July 17. If this schedule is held, the second draft will be prepared by September 15, 1970.

APPENDIX A

Summary of First Panel Meeting

Summary of the First Meeting of
the Advisory Panel on Design Criteria
for Spacecraft Solar Cell Arrays

Washington, D.C.

May 25-26, 1970

On May 25 and 26, 1970 the ad hoc advisory panel on Solar Cell Array Design Criteria met to review and critique the scope and content of a proposed outline for a monograph developed by Exotech. The objectives of the meeting also included the development of recommendations by the panel concerning pertinent references and other information sources which should be used in the development of the monograph.

The panel members in attendance were as follows:

M.J. Barrett	Exotech Incorporated
R.F. Bohling	NASA Headquarters
D.J. Curtin	Comsat Laboratories
R.G. Downing	TRW Systems
M.B. Hornstein	Exotech Incorporated
R.F. Julius	S.J. Industries
R.G. Lyle	Exotech Incorporated
H. Oman	The Boeing Company
P. Rappaport	RCA
S. Schalkowsky	Exotech Incorporated
P.D. Stabekis	Exotech Incorporated
E.J. Stofel	Aerospace Corporation
E.F. Zimmerman	Heliotek

Representatives of the Space Power Technology Branch, Goddard Space Flight Center and photovoltaic specialists from the Jet Propulsion Laboratory were invited but did not attend this meeting.

Monday, May 25, 1970

The meeting was called to order at 9:10 a.m. By Robert Lyle who introduced and welcomed the participants and spoke concerning the objectives of the meeting, mentioned above. Sam Schalkowsky then briefly told the participants about Exotech's background and activities in the NASA Design Criteria Program and emphasized the important role of the panel in

assuring relevance and validity of the technical content of the monographs.

Ray Bohling followed with a summary of the objectives, organization, accomplishments and on-going and planned activities of the NASA Program for Developing Design Criteria Monographs. Examples from completed monographs were cited to demonstrate effective techniques for communicating concise information on design criteria and recommended practices. In response to questions from panel members, Ray indicated that the monograph will probably be issued as a NASA SP-document in about mid-1971 and that the objective is to develop a monograph that will be timely in its technical content and remain relevant for as long as possible. The program recognizes and provides for updating of a monograph when the advancing state-of-the-art causes it to become obsolescent.

The next order of business was the introduction of the proposed scope and outline for the monograph prepared prior to the meeting. The panel members agreed that the central theme of the monograph should be the arrays of solar cells with emphasis on the capabilities and limitations of silicon cells and detailed coverage given to the following aspects of design problems:

- Energy conversion mechanism and efficiency
- Alternatives and methods for optimizing electrical characteristics
- Alternatives of mechanical and electrical configuration design and their effects on the overall performance of the solar cell system
- The environmental factors which affect the performance and reliability of solar cells, and the concepts and techniques of design, fabrication, evaluation and testing which deal with environmental effects.

A general outline for the monograph (Attachment #1) was introduced as an aid to the development of recommendations by the panel members concerning the content of the monograph in support of the designated scope.

Following a break for lunch, the panel reconvened and began a detailed consideration of the sections and subsections comprising the

state-of-the-art information pertinent to design criteria for solar cell arrays. Consideration of historical background began with a suggestion that a table might be developed which would show the reader what varieties of solar cell arrays had been flown and give an indication of the time sequence of development of the various types of arrays. Speaking of some of the earliest spacecraft applications of solar cells, mention was made of the Explorer II and Vanguard I. RCA made the cells and covers which were then assembled by the Signal Corps. Efforts should be made to document the development of the array for Vanguard I, as well as for Explorer II, a model of which is on exhibit at the Smithsonian Institution.

It was pointed out that the problem of radiation damage to solar cells was considered rather early in the history of spacecraft applications and the subject had also been extensively studied because of the use of solar cells in the atomic battery application for conversion of energy from a radiation source. It was noted that Van Allen actually used observed degradation of solar cells to confirm his identification of the earth's radiation belt. The Starfish event which was cited as important in the experience and background concerning radiation damage was covered rather extensively in the second photovoltaic conference held in Washington. The existence of large fluxes of low energy protons was also demonstrated by the effects observed in the uncovered solar cells flown on Relay I and II.

Two sources were suggested for summary information concerning the historical development of solar cell applications in spacecraft: the TRW space log, and the documentation of programs developed by Heliotek, which may include descriptions of the types and quantities of cells flown in various missions.

Another point of interest cited in the development of solar cell design is the fact that the improvement of cell performance as observed under artificial lighting does not necessarily correlate with improved performance in a space environment. The basis for this was found to be that the junction depth should be selected in consonance with the solar illumination spectrum in space, not with the spectrum of a laboratory simulator. This comment opened the discussion to the methods used to measure junction depth. The methods mentioned were lapping of the cell at

an angle, analysis of the spectral response, and measurement of the cell's sheet resistance.

The discussion then returned to the topic of radiation damage and the methods developed to enhance cell performance in the radiation environment. It was observed that the conversion from p/n to n/p cells to enhance radiation resistance was a U.S. achievement. The Russians were committed to the use of n/p cells prior to that time but the reason was that they had not developed a suitable process for making p/n cells as easily. It was noted that the next innovation for enhancing radiation resistance was the increase in base resistivity. It was noted that the base resistance of present day solar cells is about 10 ohm-centimeters because higher values introduce resistance effects in the cell and the voltage drops. References related to the work in base resistivity are to be found in the proceedings of the Photovoltaic Specialists Conferences, e.g., reports prepared by Eugene Ralph.

It was suggested that the section on historical background should note the change in design approach from shingles, used until about 1962, to flat-, or flush-mounted cells used subsequently. The result was an improvement in thermal response. It was suggested that Nimbus I may have had the first flat mounted cells and that documentation of this may be found in the proceedings of the Cocoa Beach conference. It was noted that the Pegasus satellites, built at about the same time, had flat mounted cells and it was suggested that contact be made with Ken Hanson for additional details about this.

Next topic discussed was the history of the problems and developments of solutions concerning the accommodation of thermal expansion and contraction in solar cell modules and arrays. A brief review was made of the history of the selection of adhesives and the methods for using them. The experience with the satellites Intelsat II F 4, ATS I and GGTS were cited as pertinent to the developments in this problem area. A suggestion reference on the topic is the paper by George Wolf given at the AIAA meeting in Los Angeles. On this topic of thermal problems it was suggested that mention be made of the need for identification of the thermal range for each type of interconnect. The paper given by Lubarsky at the AIAA

meeting in Los Angeles was suggested as a reference. Documentation of problems in this area with the lunar orbiters has been promised by Ken Hanson.

It was suggested that the paper by Abbott which summarizes experience with large solar arrays be obtained for useful information in this section on historical background. The paper was presented at the AIAA meeting in Washington in September 1969.

A brief discussion concerning the bonding of contacts to solar cells indicated that soldering of silver-titanium contacts continues as the state-of-the-art technique. Ultrasonic bonding has been demonstrated successfully (Heliotek) and there is continuing interest in the development of welded (ultrasonic) aluminum contacts.

The next topics considered were related to the size and weight characteristics of solar cells, modules and arrays. It was noted that the weight of an array is related to stiffness requirements as a result of spacecraft resonant frequency and, in some cases, the dynamic environment during launch. About 75 percent of the weight of lightweight arrays is accounted for by solar cells and coverslides. The development of integral covers is a current area of work directed to the reduction of weight in an array. The integral covers may also provide relief from the difficulties of very close dimensional tolerances required so that coverslides completely cover but do not overhang the solar cell.

Mention was made of on-going work in Great Britain to develop covers of cerium-doped microscope glass. A testing program is currently underway. Denis Curtin offered to provide a copy of a report by Fred Treble on this work.

The most common size of solar cells has been 1x2, and it was pointed out that most tooling in the industry can readily accommodate sizes that are integer multiples of two centimeters. Dendritic cells have been alleged to be less costly than conventional cells but actually are not. The 2 x 4 cm cell is a common size which can be obtained by diagonal slicing of an ingot. A possible indication of change in cell size is seen in the trend of the semiconductor industry to 3 inch wafers which may eventually

bring about 3x3 inch solar cells. Work done at Texas Instruments indicates the most economic size for solar cells will be 3x3 inches. It was noted that for body-mounted arrays the spacecraft geometry may be very important to the selection of cell size.

Following a break for lunch the panel reconvened and entered into discussion concerning the environmental factors which must be accounted for in solar cell array design. The factors of the flight environment suggested for treatment in the monograph included: corpuscular radiation, micrometeoroids (considered negligible by the panel), temperature, solar illumination, ultraviolet, vibration, and engine gases. It was suggested that consideration should also be afforded the pre-flight environment, particularly humidity, temperature, and contamination.

It was noted that recent results of studies of thermal effects will be presented at the next meeting of photovoltaic specialists at Seattle in August. A suggestion was made that the treatment of thermal environment and effects in the monograph should include emphasis on the importance of absorptivity and emissivity, and typical ranges of α and ϵ values should be given. The effects of rapid temperature changes, such as occur in solar occultation, require special consideration in the design of power systems with output at a fixed voltage; the effects and compensating design techniques should be covered in the monograph.

The discussion turned to the information on adhesives that should be presented in the monograph. It was emphasized that the choice of adhesive for a solar cell assembly should be made on the basis of estimated environmental exposures associated with the particular mission for which an array is being designed. The established types of adhesives for solar cell applications include Dow Corning types 182 and 184 and RTV-602. A new adhesive based on a formulation similar to types 182 and 184 is reportedly being developed at the Goddard Space Flight Center. It was noted that the Dow Corning and RTV types of adhesives are not compatible during application and cure. When the adhesive bond between solar cell and substrate is curing it gives off vapor that inhibits cure of coverslide adhesives. These two bonding processes generally should be separated by several days in time to avoid chemical interference.

Background information and data on the use of adhesives for bonding cells to substrates and covers to cells were offered by Richard Julius. He cited as major factors in the problems of adhesive bonding the temperature, humidity and contaminants (dust) during application and cure. There are no industry or other specifications for environmental control during adhesive bonding operations; however, proper application of adhesives requires such control.

Additional information on adhesives should be obtained from the Stanford Research Institute Report prepared for JPL and titled "Polymers for Spacecraft Use". Contact should be made with J. Hanos of Comsat and R. Yasui of JPL for further inputs on this topic.

Testing of cells, modules and arrays was the next topic taken up by the panel. The distinction between qualification and acceptance testing was cited and should be made clear in the monograph. For purposes of qualifying an array for a particular spacecraft or mission, severe test conditions are imposed (in some cases test-to-failure is required). The tested items that survive are not subsequently installed on a spacecraft but have served their purpose by demonstrating the strengths (and weaknesses) of a particular design. Acceptance testing involves flight-qualified components being subjected to conditions which will demonstrate flight readiness and acceptability of actual mission hardware.

Qualification tests should be performed as early as possible in the program. The objective is to assure that a qualified design is achieved before the production of panels for use on the spacecraft. It was noted that, of the required mechanical tests, vibration is commonly the most severe. A case was cited in which the IDSCP's built to the specifications for Atlas Centaur launch vehicles were reassigned for an application using a Titan 3 launch vehicle. During acoustic testing, 15 of the 16 panels tested failed. The remainder of the previously accepted panels had to be reinforced for this application.

It was suggested that the monograph should contain discussion of the use of primary standard cells, balloon-flight calibration techniques and other methods presently used to measure cell and array efficiencies.

The final topic touched upon in this session of the panel meeting was the impact on solar cell array design, and methods for accommodating, of those mission-oriented design requirements on a spacecraft which affect practically all systems, e.g., magnetic cleanliness requirements. This particular area of requirements has been treated in another design criteria monograph prepared by Exotech. It will be handled in this monograph by appropriate references. No other systems interface problems were suggested for coverage other than the power conditioning and storage, and structural configuration considerations identified at the outset of the meeting.

Tuesday, May 26, 1970

/ The remainder of the meeting of the ad hoc advisory panel on solar cell array design criteria took place during the morning of 26 May 1970 at NASA Headquarters.

The session was opened by the chairman with a request for suggestions concerning the essential elements of solar cell array performance requirements which would serve to keynote the criteria section of the monograph. The suggestion which all panel members subscribed to is that the design objective can be defined in terms of an end-of-mission power requirement which can be translated into a practicable design by working back through the hierarchy of mission and spacecraft requirements and constraints.

It was recognized that the requirements and constraints commonly imposed between the ultimate objective of the array design (e.g., end-of-life power, or watts per pound or per dollar) and the details of the operating characteristics and physical configuration, comprise the design criteria which should be reflected in the monograph. Several of the panel members offered to submit lists of factors which have been identified in their organizations as essential considerations for effective design.

The pertinent factors include the broad range of considerations from the design of interconnects of series and parallel strings of cells to provide the desired electrical power and characteristics throughout the mission, to the selections of cells, substrate, coverslips, adhesives, etc., to ensure reliable performance in the mission environment.

Design considerations specifically recommended for inclusion in the Criteria section included:

voltage	Design the operating voltage at the point of maximum power of the degraded cell, under the worst temperature conditions; voltage should be high enough to charge batteries, especially in low orbits where much recharging is necessary; in the later stages of long missions, about 35% of the energy required for battery charging is lost due to inefficiency, thermal losses, etc; most spacecraft are designed for power at 28 volts dc.
load	Sizing of solar cell arrays should permit a 10% increase in power needs as the design matures; load growth of this magnitude is not uncommon particularly when the spacecraft is the first of a new series.
angle of illumination	Particularly important when operating on the knee of the solar cell curve where loss can be steep.
temperature	Body-mounted arrays have to operate warm, because of the temperature requirements for batteries and other equipment within the spacecraft. When paddles are used the cells can be kept cool by use of white paint on the back of the paddles, and any exposed front area. Temperature can generally be controlled by placing a red-reflecting coating or coverslide on the cell.
cell and circuit design	Importance of dimensional tolerances; tolerances on contacts; α and ϵ values; cell matching for parallel circuits; parallel-series circuits for long-term reliability; use of parallel connected diode to prevent significant reverse voltage due to an 'open' in a cell or contact.
adhesive	Thermal properties, glass-transition temperature; effects of aging before application; use of primers; tests for adhesion.

- . coverslide Matching of thermal expansion characteristics to solar cell; spectral filter effects; dimensional fit to solar cell.

- . substrate Minimization of thermal coupling with the spacecraft, rigidity, and weight are primary considerations. Vibration and acoustic noise at liftoff are among the most serious problems. Preferred substrates are: honeycomb with aluminum, epoxy fiberglass, and a carbon filament face sheet.

Another problem area discussed by the panel and recommended for treatment in the monograph has to do with calibration and performance testing of cells. All solar simulators tend to degrade through accumulation of contaminants, filament burnout, etc., and require maintenance and frequent calibration with a standard cell (e.g., balloon-flight calibrated) and cut-off filters. The common sources of errors in testing are the illumination source, test instrumentation, and the calibration standard. Performance testing is often done with "coupons," e.g., 8 by 3 series-parallel connected array of cells mounted on a panel. For mechanical, vibration and thermal tests, the specimen panel is often comprised of "dummy" cells of aluminum.

Performance of an array may be adversely affected by shadowing. This problem may arise rather late in the design process because of a revision to the spacecraft or experiment package configuration adding a boom, antenna or other extended structure which may in some spacecraft orientations interfere with illumination of the array. Close attention to the potential "growth" of such interference sources is warranted.

Repairability of the array is another important consideration of design. Several panel members commented on the need to keep simple the processes of partial disassembly of the array for inspection and repair work.

The last few minutes of the meeting were devoted to another discussion period on the history of operational failures in solar cell arrays to identify any known events which could be profitably cited to emphasize the need

for using preferred design practices. The inclusion of such accounts in a monograph also serves to emphasize the validity of recommended precautions in design, development, testing, and the mating to the spacecraft of solar cell arrays. Incidents with Nimbus and Mariner II were cited and the panel members were requested to search for leads to other documented flight experience.

The meeting of the panel was adjourned at noon on Tuesday May 26, 1970 with a tentative schedule for the next meeting to be on August 7, immediately following the Photovoltaic Specialists Conference in Seattle, Washington.

(ATTACHMENT 1 - to summary
of panel meeting)

Proposed General Outline
Design Criteria Monograph
Spacecraft Solar Cell Arrays
May 25, 1970

Foreword

1. Introduction
2. State-of-the-Art
 - 2.1 Historical Background
 - 2.2 Solar Cell Description and Model (General)
 - 2.3 Flight Experience
 - 2.4 Design and Mounting of Solar Cell Arrays
 - 2.5 Effects of Environment
 - 2.6 Test and Evaluation
 - 2.7 Summary
3. Criteria
 - 3.1 Physical Properties and Performance Requirements
 - 3.2 Effects of Environment
 - 3.3 Evaluation of Performance
4. Recommended Practices
 - 4.1 Design and Mounting for Required Performance
 - 4.2 Accommodation of Environmental Effects
 - 4.3 Evaluation and Tests

APPENDIX B

Content Development Board's for First Draft Monograph

CONTENT DEVELOPMENT BOARDAPPLICABLE TO: ☐ INTRODUCTION ☐ STATE OF THE ART ☐ CRITERIA ☐ RECOMMENDED PRACTICE ☐ APPENDIXSECTION: Historical Background SUBSECTION: _____TOPIC: History of Photovoltaic Devices/Development of Solar Cells

THESIS (what point are we making):

The present-day silicon solar cell grew out of studies of the photovoltaic effect.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Discovery of photovoltaic effect by Becquerel
2. Development of theory
3. Development of pure semiconductors
4. Space applications of solar cells

SOURCES OF INFORMATION:

Wolf's RCA review
Paul Rappaport's collection of historical papers

TO BE PREPARED BY:

CONTENT DEVELOPMENT BOARD

APPLICABLE TO: ☐ INTRODUCTION ☒ STATE OF THE ART ☐ CRITERIA ☐ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: Flight Experience SUBSECTION: _____

TOPIC: Flight History

THESIS (what point are we making):

Solar cells have been used since early days for power supplies on unmanned satellites.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. First use (on Vanguard and Explorer 2)
2. Effects of the Starfish Explosion
3. Proton effects (ATS-1, IDSCP, etc.), coverslide gaps
4. Extensions to high power applications (positionable paddles)
5. Mariner II

SOURCES OF INFORMATION:

TO BE PREPARED BY:

Transcript of the Photovoltaic Specialists Conference, Washington, D.C., April 1963
An analytical review of the ATS-1 solar cell experiment (NAS-5-11663)

CONTENT DEVELOPMENT BOARD

APPLICABLE TO: ☐ INTRODUCTION ☒ STATE OF THE ART ☐ CRITERIA ☐ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: Solar Cell Characteristics

SUBSECTION: _____

TOPIC: Energy Conversion by Solar Cell

THESIS (what point are we making):

Photons of light of wavelengths 0.4 - 1.1 microns provide energy to a solar cell for conversion to electricity

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Solar cell configuration (physical appearance)
2. Photovoltaic effect
3. Function of each element and interfaces with adjacent cells
- 4.

SOURCES OF INFORMATION:

Solar Cell Handbook
Sze
Grove

TO BE PREPARED BY:

CONTENT DEVELOPMENT BOARDAPPLICABLE TO: ☐ INTRODUCTION ☒ STATE OF THE ART ☐ CRITERIA ☐ RECOMMENDED PRACTICE ☐ APPENDIXSECTION: Solar Cell Characteristics

SUBSECTION: _____

TOPIC: Electrical Output of Solar Cells

THESIS (what point are we making):

Light causes cell to act as a current source

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Conversion Efficiency
 1. present
 2. trend
 3. optimum
2. Diode effect
3. Effect of load in determining voltage
- 4.

SOURCES OF INFORMATION:

TO BE PREPARED BY:

CONTENT DEVELOPMENT BOARDAPPLICABLE TO: ☐ INTRODUCTION ☒ STATE OF THE ART ☐ CRITERIA ☒ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: Solar Cell Characteristics

SUBSECTION: _____

TOPIC: Size (area) of Available Solar Cells

THESIS (what point are we making):

Typical solar cells are manufactured with 1, 2, and 3 cm sides, as squares or rectangles.
Also available are dendritic cells with lengths up to 5 times their width.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Electrical parameters output current is proportional to area.
Resistance essentially constant per cm²
2. Cost vs. cell area
3. Grid design vs. cell area
- 4.

SOURCES OF INFORMATION:

TO BE PREPARED BY:

CONTENT DEVELOPMENT BOARD

APPLICABLE TO: ☐ INTRODUCTION ☒ STATE OF THE ART ☐ CRITERIA ☒ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: Solar Cell Characteristics

SUBSECTION _____

TOPIC: Effect of thickness on electrical parameters

THESIS (what point are we making):

Cell thickness affects the efficiency of a cell

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. The average collection efficiency, absorption ratio and short circuit current increase with cell thickness, but approach an asymptote at approximately 14-18 mils.
2. Practical limitations on the minimum cell thickness:
3. Thickness cells yield more power per unit area, while thinner cells retain more of their output under exposure to corpuscular radiation.
- 4.

SOURCES OF INFORMATION:

Wolf, M. and Ralph, E. L.: Effect of Thickness on Short Circuit current.

TO BE PREPARED BY:

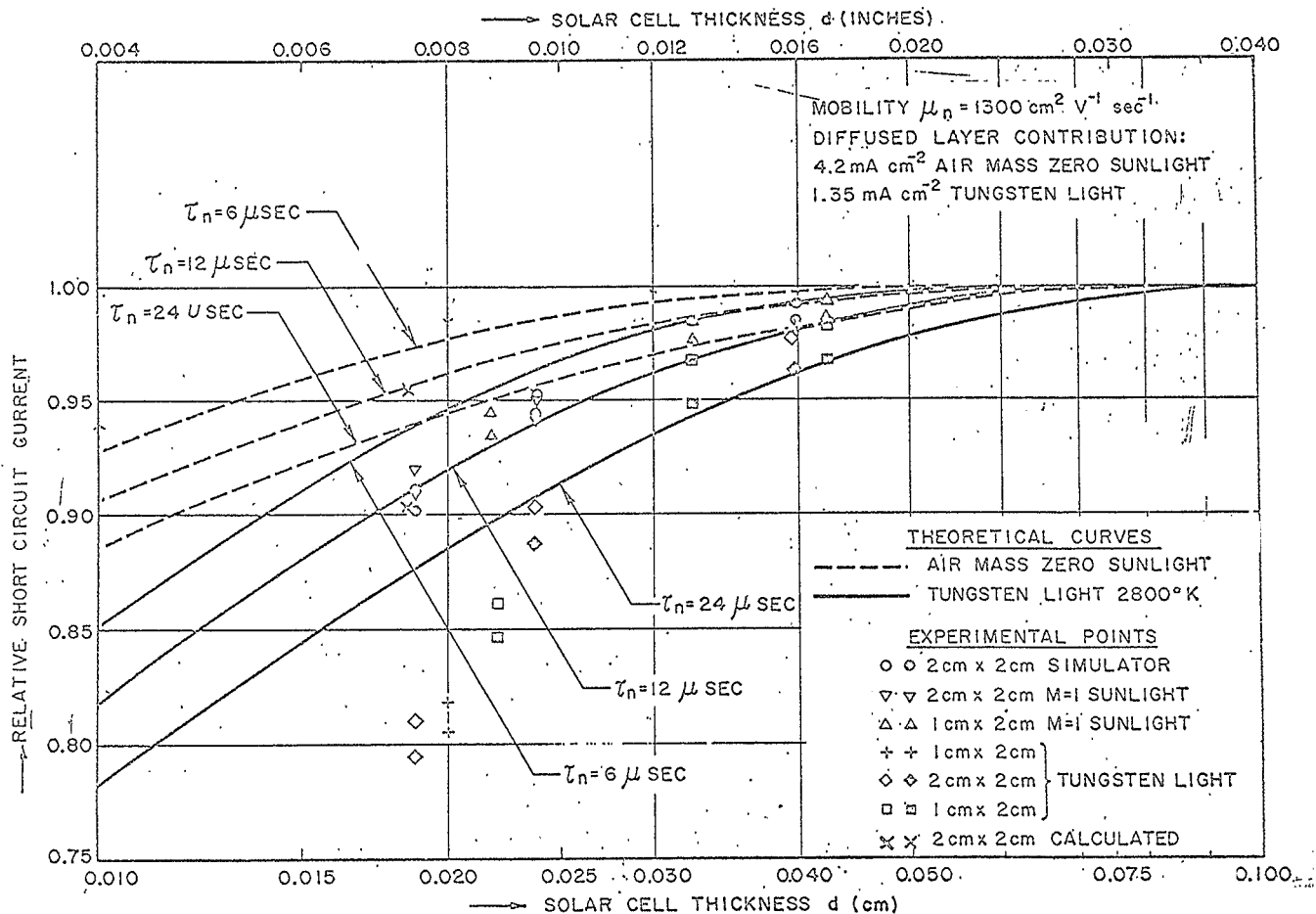


FIG. 2

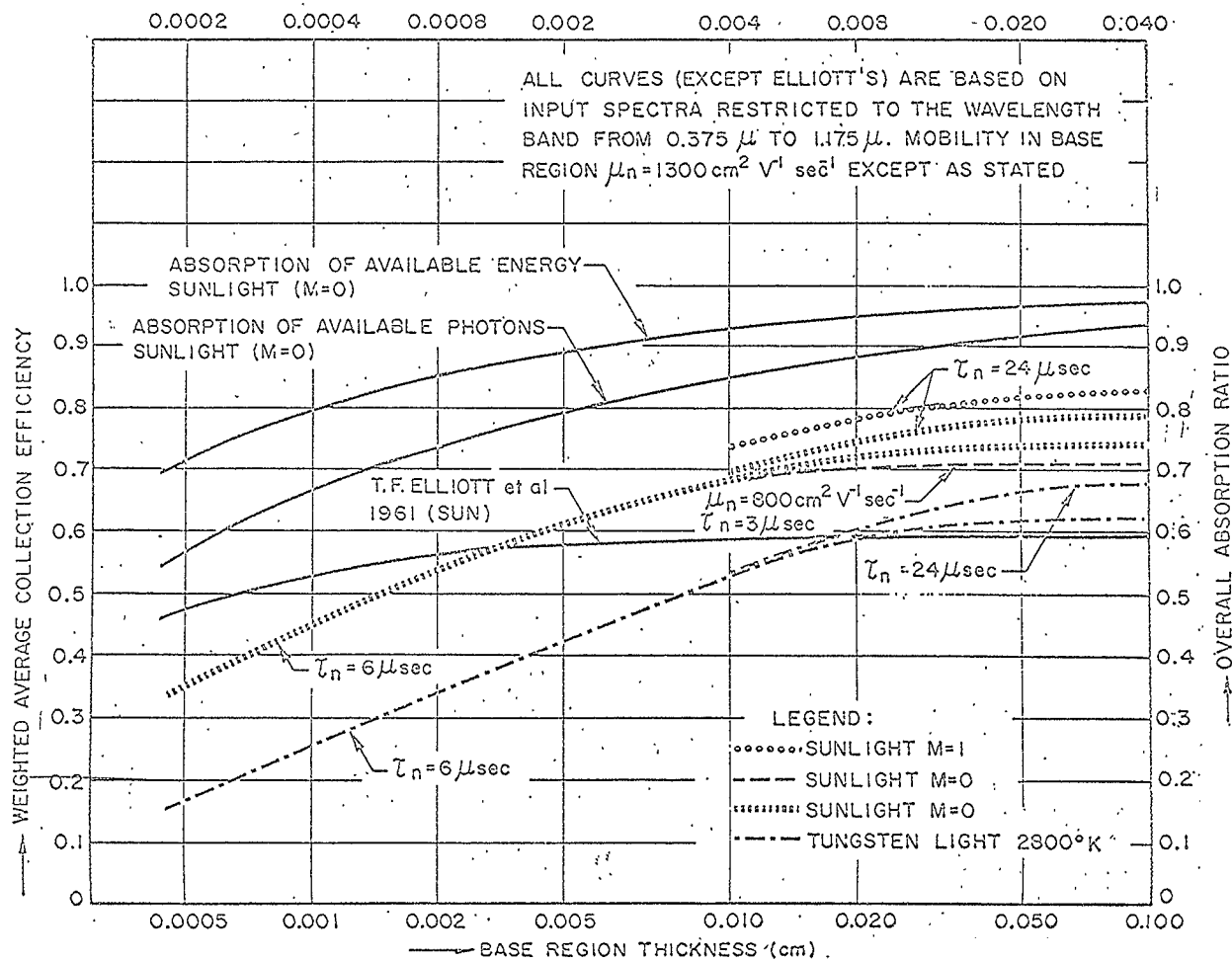


FIG. 1

CONTENT DEVELOPMENT BOARD

APPLICABLE TO: ☐ INTRODUCTION ☒ STATE OF THE ART ☐ CRITERIA ☒ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: Solar Cell Characteristics

SUBSECTION: _____

TOPIC: Weight vs. efficiency considerations

THESIS (what point are we making):

A weight-versus-efficiency tradeoff exists to permit choice of solar cells of differing thickness to obtain a given power output for a minimum weight.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

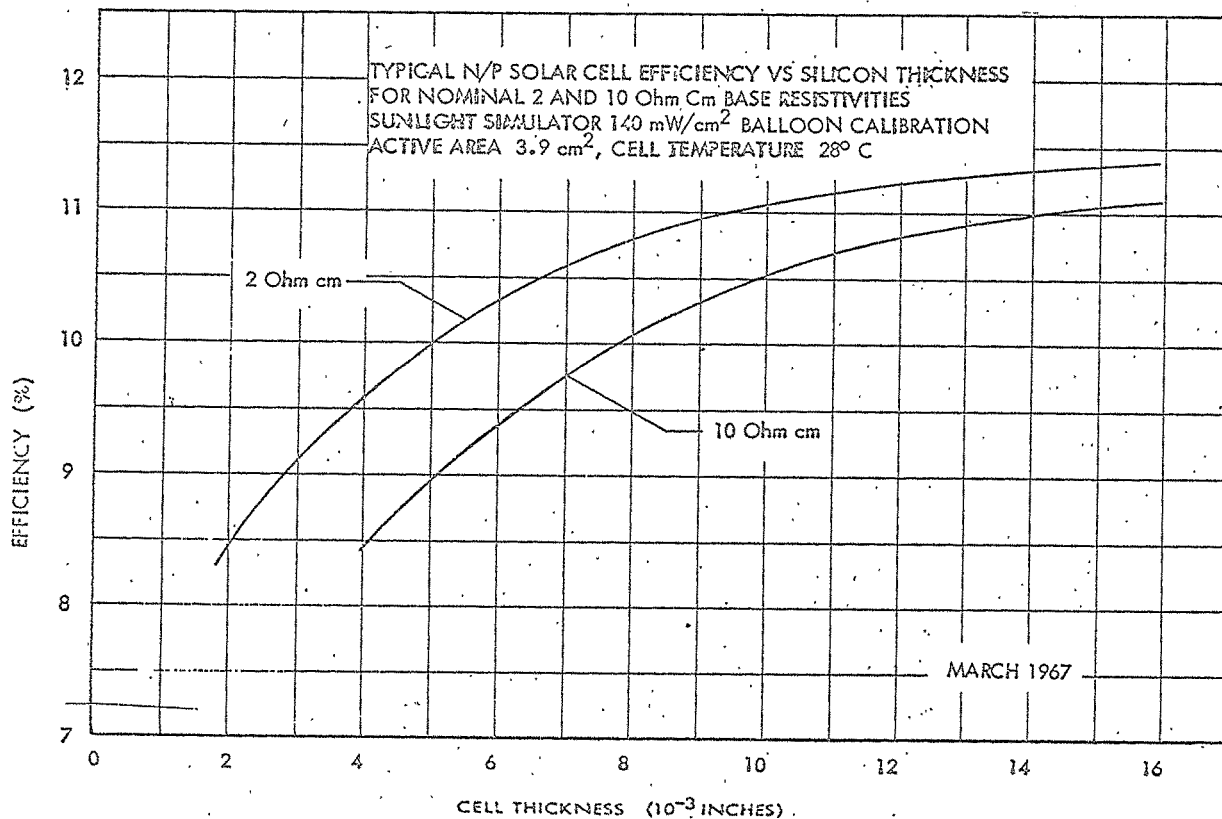
1. The output of solar cells does not increase linearly with thickness, but varies according to the accompanying figure.
2. This permits a selection of cell thickness to conform with panel area or weight requirements.
- 3.
- 4.

See attached Figure

SOURCES OF INFORMATION:

TO BE PREPARED BY:

Ralph: Performance of Very Thin Si Solar Cells
6PSC-Vol. I, pp.104



6th PS, vol. 1

(CRolph)

CONTENT DEVELOPMENT BOARD

APPLICABLE TO: ☐ INTRODUCTION ☒ STATE OF THE ART ☐ CRITERIA ☒ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: Solar Cell Characteristics

SUBSECTION: _____

TOPIC: Effect of junction depth on electrical parameters

THESIS (what point are we making):

Increasing junction depth decreases J_{sc} and P_{max} , but increases radiation resistance.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Variations in J_{sc} , V_{oc} , and P_{max} with junction depth (Table I)

Table I.

2. Surface region less susceptible to radiation damage

3. Optimum junction depth (trade-off between 1. and 2.)

4.

SOURCES OF INFORMATION:

TO BE PREPARED BY:

2nd. Quarterly Report to JPL by Exotech.

$t(\mu\text{m})$ $d(\mu)$	7	10	14
0.2	40.222	40.855	41.168
0.5	37.171	37.790	38.129
1.0	32.279	33.908	34.235

J_{sc} in mA/cm^2

$t(\mu\text{m})$ $d(\mu)$	7	10	14
0.2	.44963	.45047	.45079
0.5	.44569	.44651	.44696
1.0	.43863	.44110	.44158

V_{oc} in Volts

$t(\mu\text{m})$ $d(\mu)$	7	10	14
0.2	12.167	12.387	12.495
0.5	11.116	11.329	11.445
1.0	9.455	10.005	10.116

P_m in mW

Table 1. Dependence of solar cell parameters on cell thickness t and junction depth d , as computed from the mathematical model for an n/p solar cell in AM0 sunlight.

CONTENT DEVELOPMENT BOARD

APPLICABLE TO: ☐ INTRODUCTION. ☒ STATE OF THE ART ☐ CRITERIA ☒ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: Solar Cell Characteristics

SUBSECTION

TOPIC: General Effects of Illumination Intensity on Solar Cells

THESIS (what point are we making):

All important electrical parameters increase with increasing light intensity

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. For a given cell temperature; within the range of observations, short circuit current and maximum available power increase linearly with increasing light intensity

See attach Figs

2. Open circuit voltage decreases approximately 0.2 mV/mW/cm^2 with decreasing light intensity, down to about 60 mW/cm^2 , below that, the voltage drop accelerates.

3.

4.

SOURCES OF INFORMATION:

TO BE PREPARED BY:

Ritchie, D. W. and Sandstrom, V. D.: Multikilowatt
Solar Arrays, Conf. Record of Sixth Photovoltaic Specialist Conf.,
vol. II.

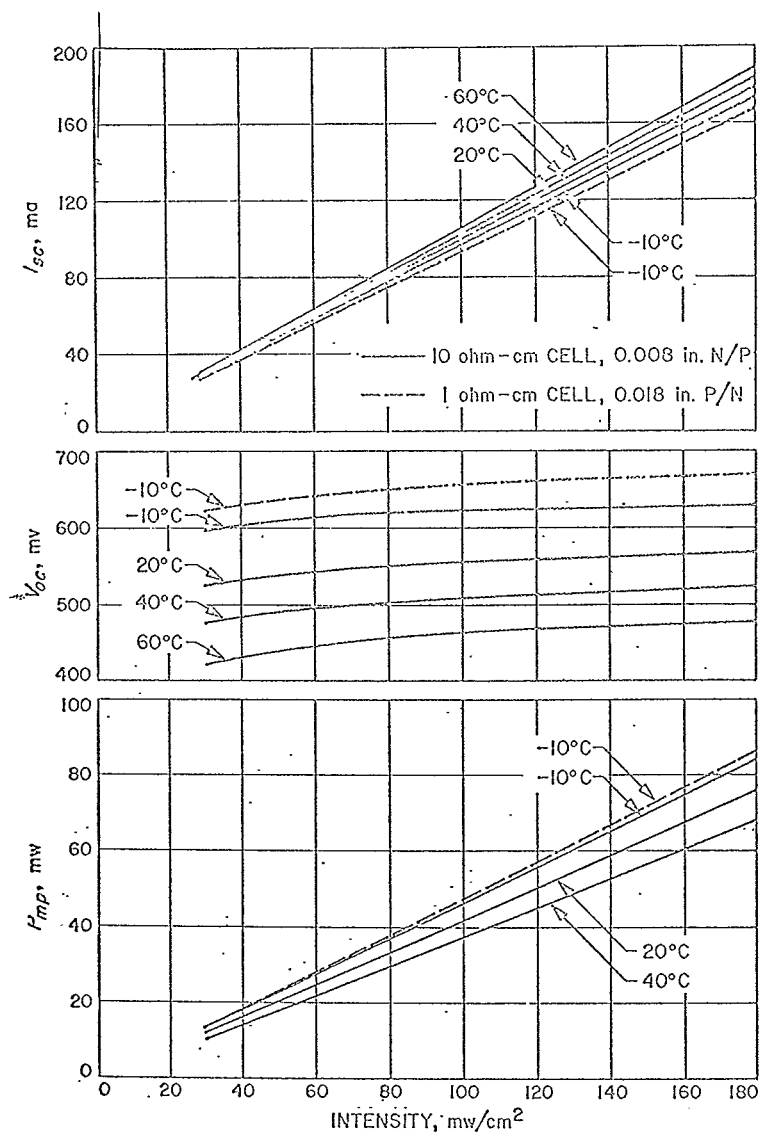


FIG. 1. A COMPARISON OF N/P SILICON CELL CHARACTERISTICS AS A FUNCTION OF INTENSITY AND CELL TEMPERATURE

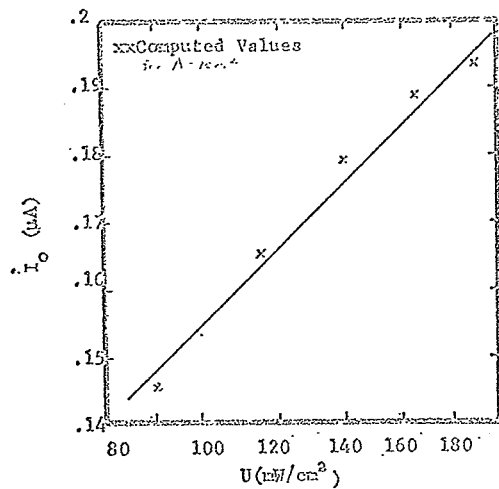


Figure 3. Variation of diode current with illumination intensity.

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SECTION: Solar Cell Characteristics

SUBSECTION: Environmental Effects

TOPIC: General Effect of Temperature on the Electrical Parameters

THESIS (what point are we making):

Electrical performance is generally poorer at elevated temperature

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. The short circuit current increases slowly with increasing temperature
2. The open circuit voltage decreases with increasing temperature, because of the exponential increase of the diode current
3. The maximum power decreases almost linearly with increasing temperature
- 4.

See attached Figures

SOURCES OF INFORMATION:

TO BE PREPARED BY:

Waddel, R. C.: Radiation Damage Shielding of Solar Cells on a Synchronous Spacecraft.

Reynard, D. L.: Proton and Electron Irradiation of N/P Silicon Solar Cells.

Barrett, M. J. and Hornstein, M. B.: Solar Cell Performance Math Model 2nd. Quarterly Report

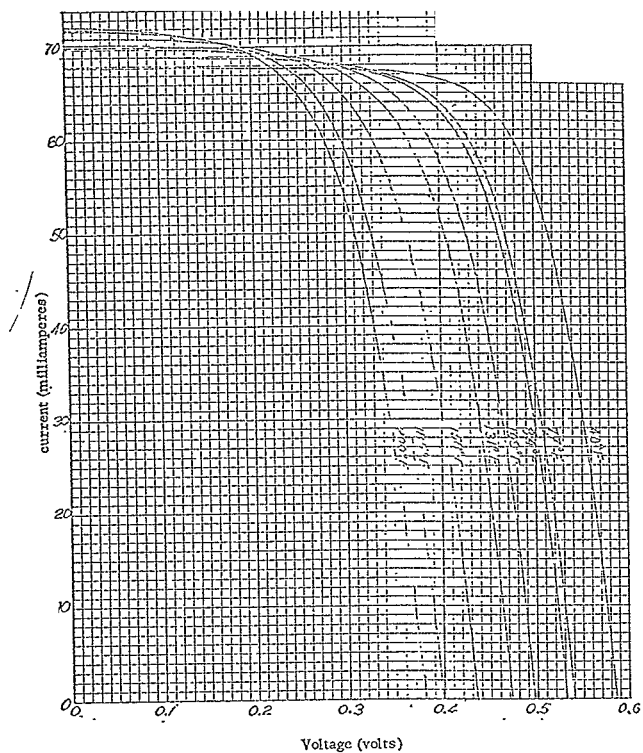


Figure 1. Current-Voltage Characteristic for Hoffman 10 ohm-cm N/P Cells at Various Temperatures, Unirradiated

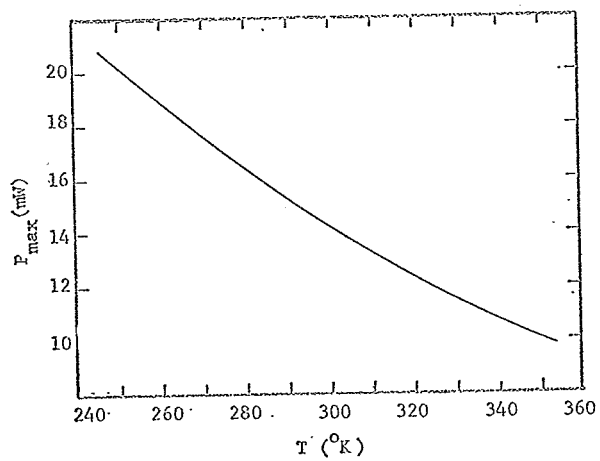


Figure 2. Temperature dependence of maximum output power

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SECTION: Solar Cell Characteristics

SUBSECTION: Environmental Effects

TOPIC: Corpuscular Radiation in Space

THESIS (what point are we making):

The existence of corpuscular radiation in space, particularly near Earth, affects long term performance of solar cells

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Geomagnetically trapped particles
2. Solar flare protons
3. Cosmic rays
- 4.

SOURCES OF INFORMATION:

Solar Cell Handbook (Exotech)
Procedures of Photovoltaic Specialist Conferences

TO BE PREPARED BY:

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SECTION: Solar Cell Characteristics

SUBSECTION: Environmental Effects

TOPIC: Effects of Proton Irradiation on Electrical Parameters

THESIS (what point are we making):

The major electrical parameters decrease with proton irradiation. The rate of decrease is a function of the energy of the proton, the flux, and the construction of the cell assembly.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. The maximum available power, the short circuit current, and the open circuit voltage all decrease with proton irradiation
2. The rate of decrease is greater for low energy particles than for particles with energy sufficient to completely penetrate the cell
3. Low flux rates allow annealing of the cell
4. Some constructions are more radiation resistant than others (e.g. lithium-doped, N/P vs. P/N coverslides, etc.)

See attached Figures

SOURCES OF INFORMATION:

Downing, R. G.: Low Energy Proton Degradation in Silicon
Solar Cells, Proc. of 5th. Photovoltaic Spec. Conf., vol. II.
B. Anspaugh, JPL

TO BE PREPARED BY:

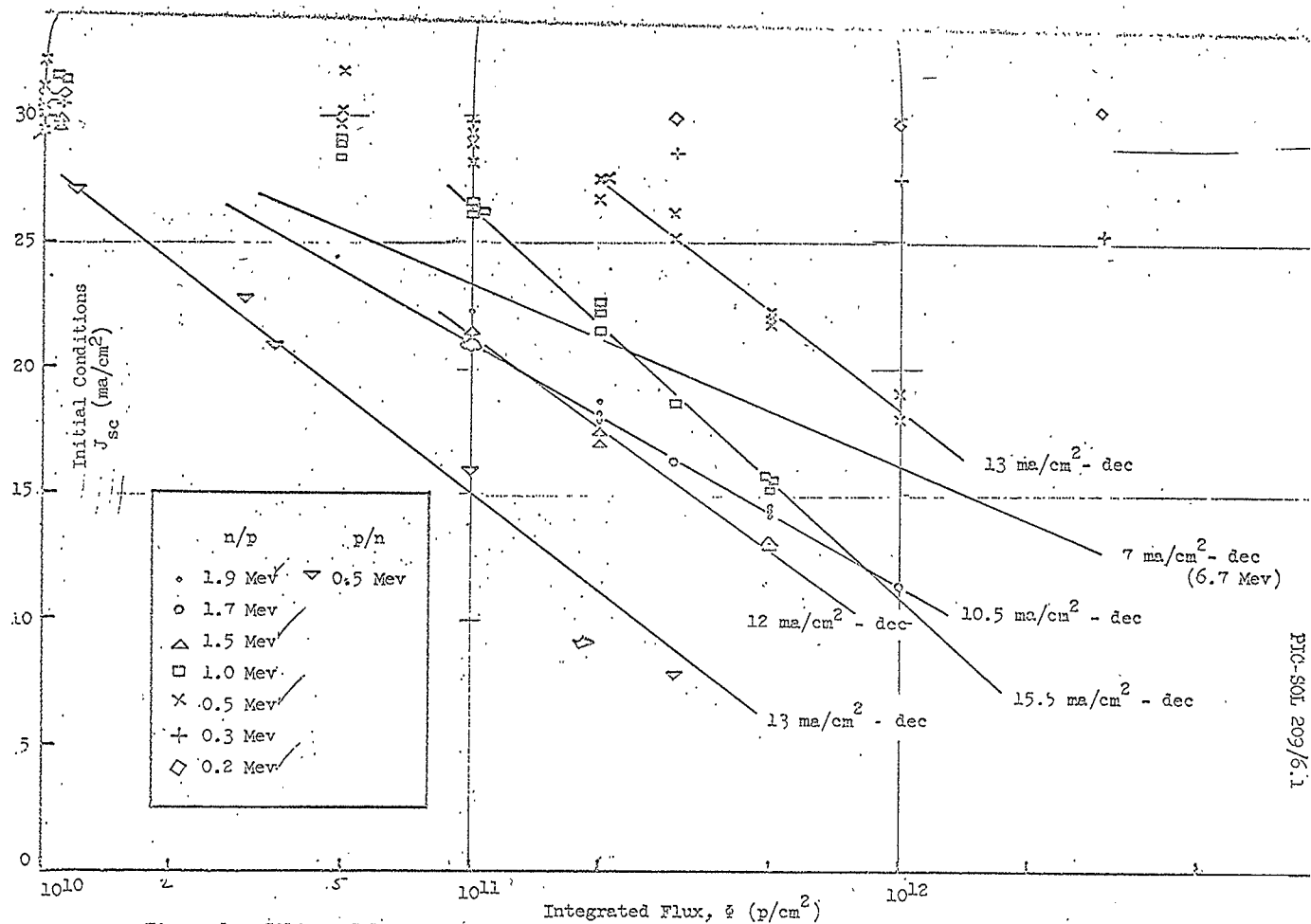


Figure 1.- Silicon Solar Cell Short-Circuit Current Degradation Under Low Energy Proton Irradiation

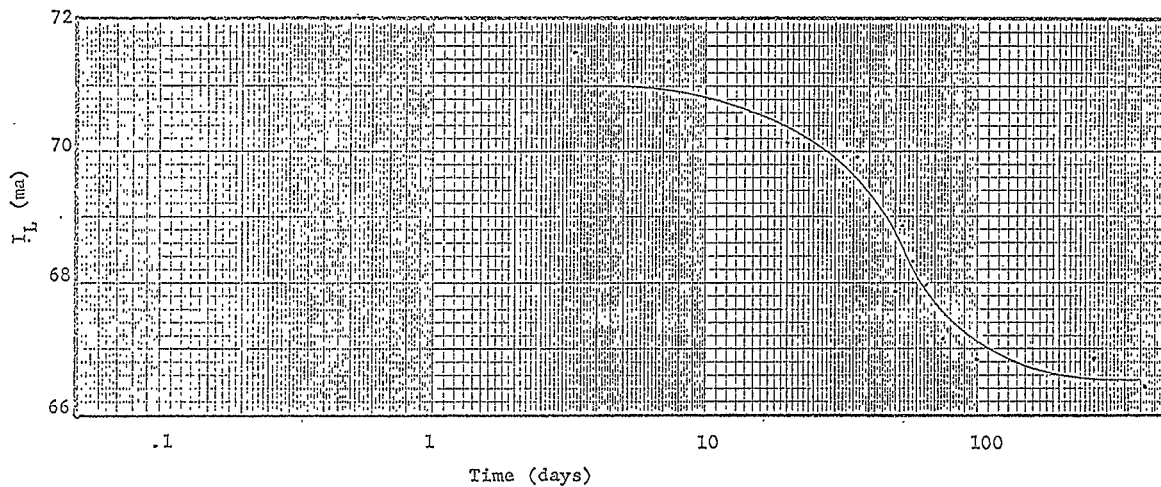


Figure 2. Cell 20 of ATS-1 solar cell experiment photovoltaic current I_L corrected for illumination intensity, aspect angle, and temperature vs. time after launch.

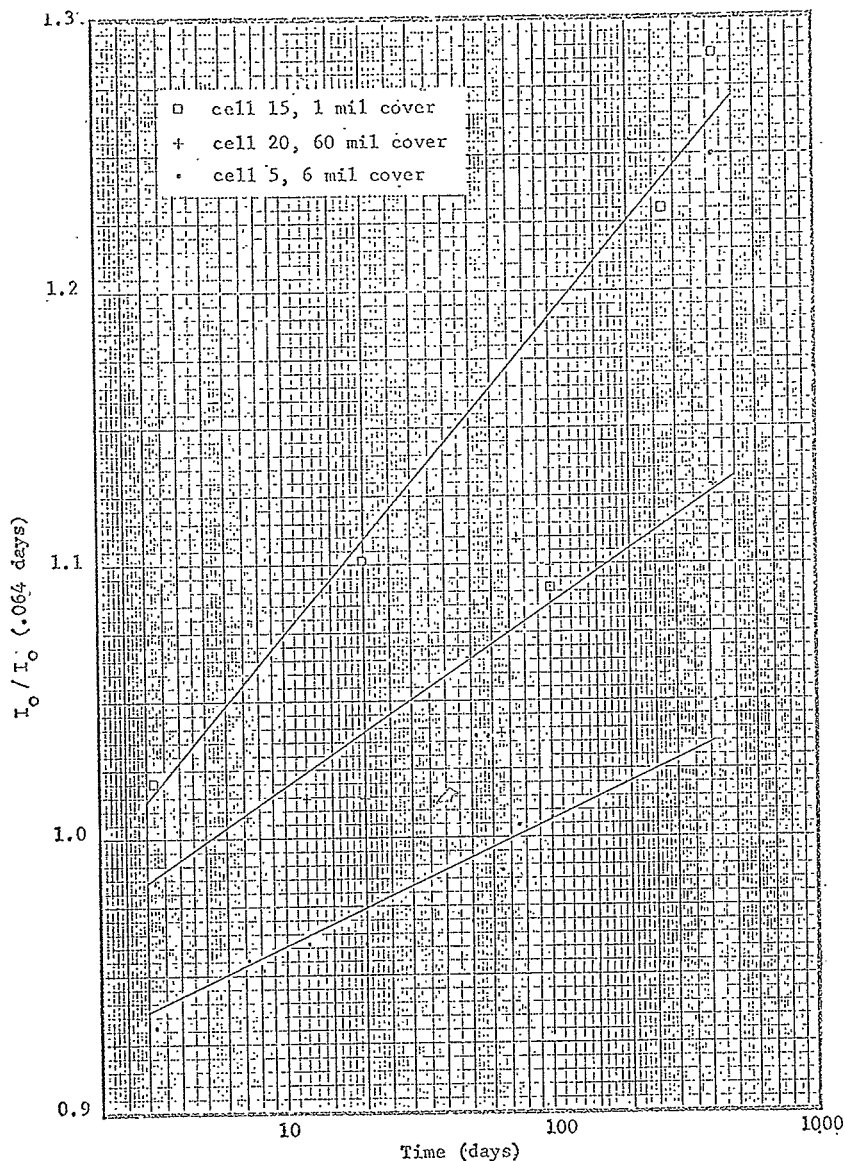


Figure 3 Normalized diode current I_o for three 10Ω - i n/p silicon solar cells with various shield thicknesses vs. time after launch.

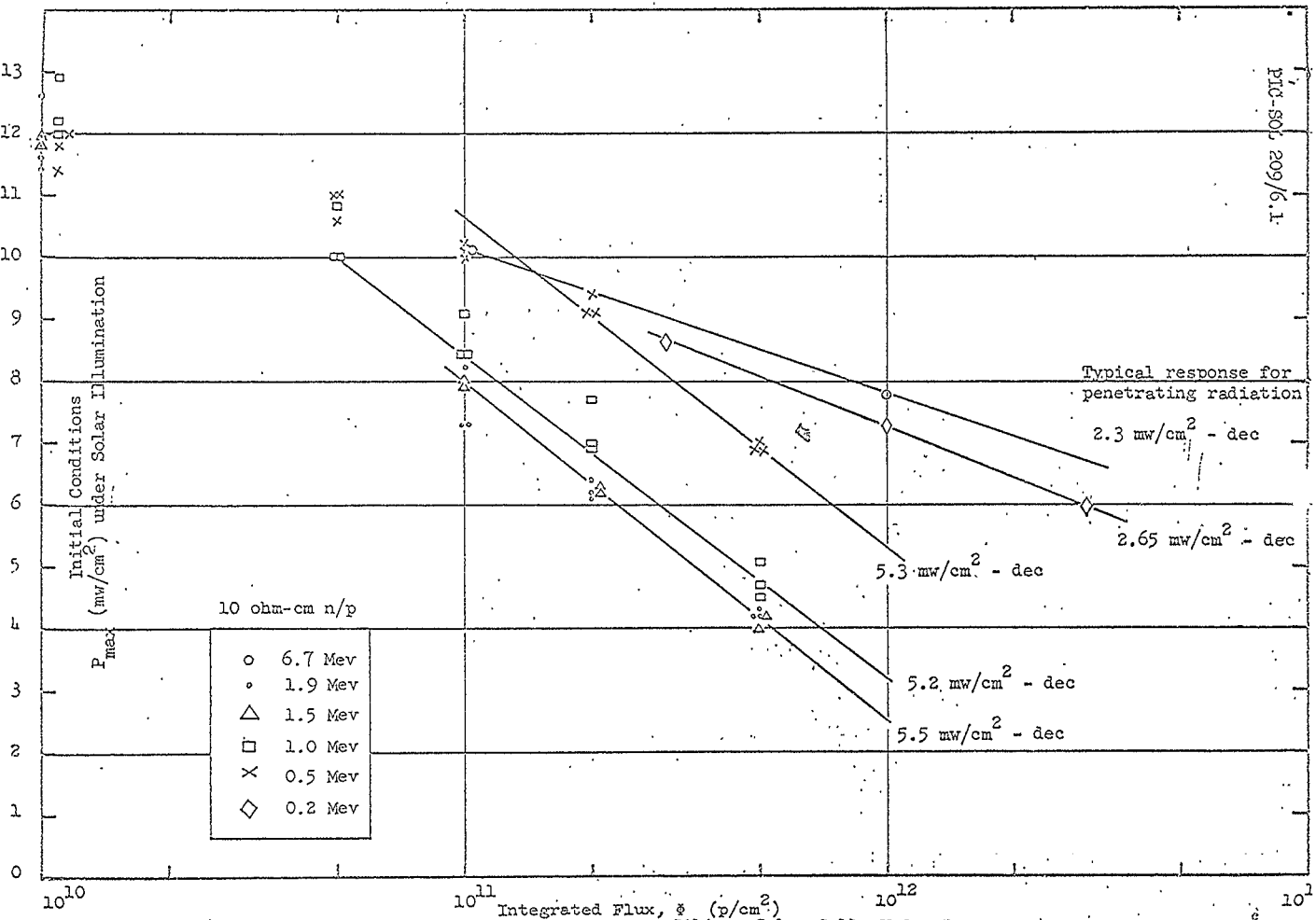


Figure 4 - Degradation of Maximum Power Output for Silicon Solar Cells Under Low Energy Proton Irradiation

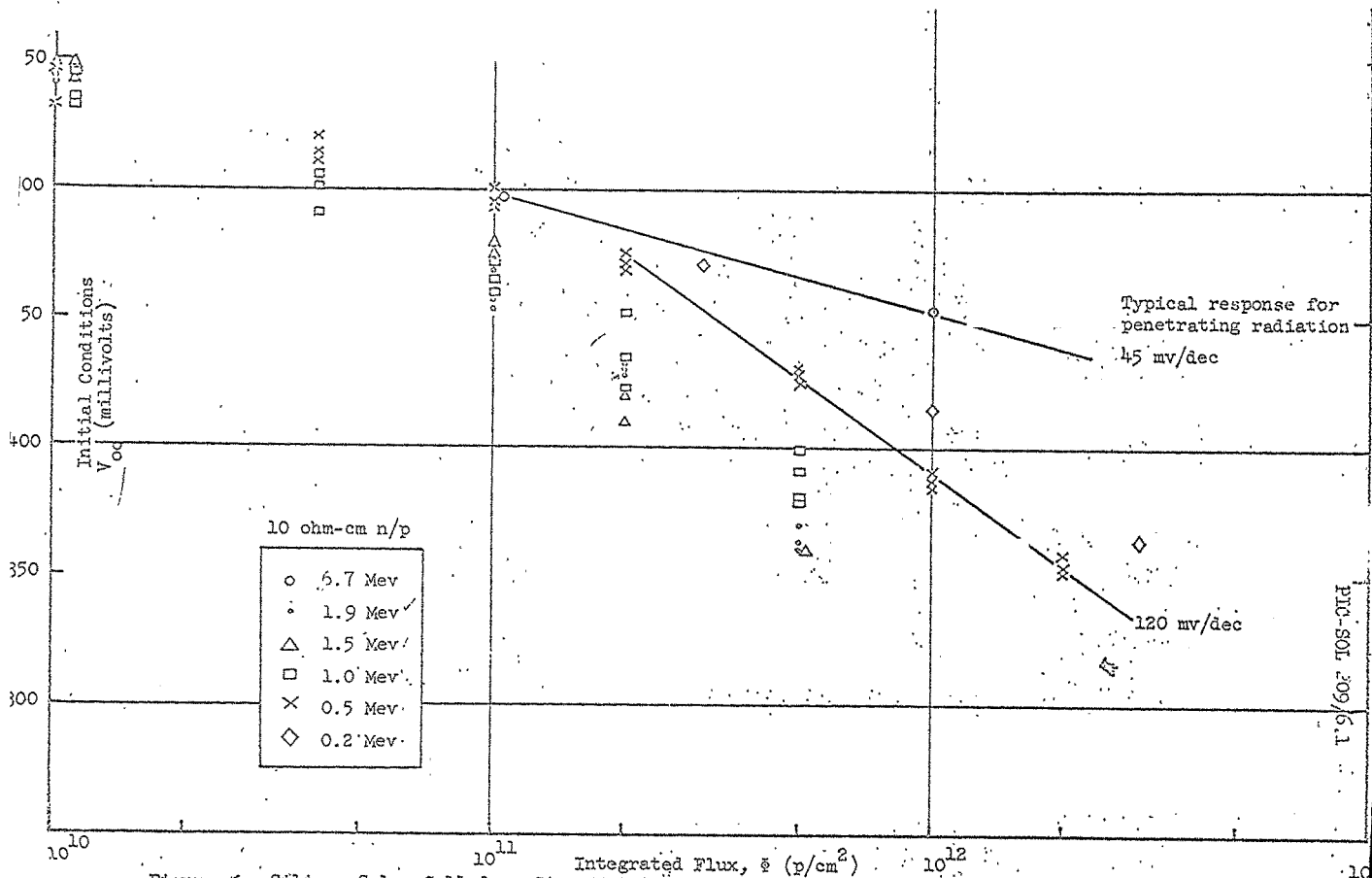


Figure 5 - Silicon Solar Cell Open Circuit Voltage Degradation Under Low Energy Proton Irradiation

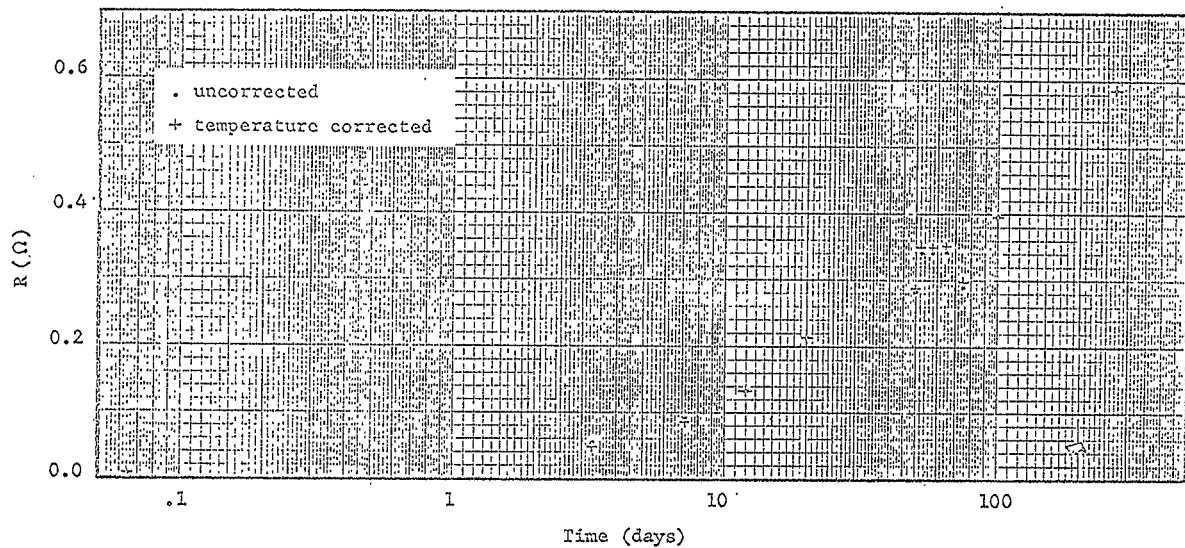


Figure 16. Cell 20 computed series resistance R vs. time after launch

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SECTION: Solar Cell Characteristics SUBSECTION: Environmental Effects

TOPIC: Effects of Electron Irradiation on Electrical Parameters

THESIS (what point are we making):

Electron radiation in space degrades the electrical output of solar cells a few percent per year in typical cases

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. Short-circuit current is affected most noticeably
2. N/P solar cells are less affected than P/N solar cells
3. Increasing base resistivity decreases the sensitivity to radiation
- 4.

SOURCES OF INFORMATION:

Solar Cell Handbook (Exotech)
Procedures of Photovoltaic Specialist Conferences (6,7 & 8)
B. Anspaugh, JPL

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APPLICABLE TO: ☐ INTRODUCTION ☒ STATE OF THE ART ☐ CRITERIA ☒ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: Solar Cell Characteristics

SUBSECTION: Environmental Effects

TOPIC: Coverslides

THESIS (what point are we making):

Coverslides provide optical and thermal matching (They also provide shielding).

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Optical matching
 1. reflection phenomena.
 2. use of filters (U.V., I.R.)
2. Thermal matching
 - α/ϵ ratio
3. Radiation shielding
4. Methods of attaching coverslides (adhesives, corner darts)

SOURCES OF INFORMATION:

Corliss: Scientific Satellites
Reynard: Handbook Ref. 239
ATS-1 Report

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SECTION: Solar Cell Array Construction

SUBSECTION: _____

TOPIC: Mounting of Arrays

THESIS (what point are we making):

Arrays are mounted either on the spacecraft body or on a positionable paddle

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Body mounting (Figure 1)

Attached Figures

2. Positionable paddles for 100-500 W (Figures 2 & 3)

3. "Fold-out" or "roll-out" paddles for higher power (Figures 4-6)

4. Panel construction trade-off of breakage potential vs. ease of construction.

SOURCES OF INFORMATION:

TO BE PREPARED BY:

1. Barrett and Stroud: ATS-1 Report
2. Corliss: Scientific Satellites
3. Ritchie and Sandstrom: Multikilowatt Solar Arrays

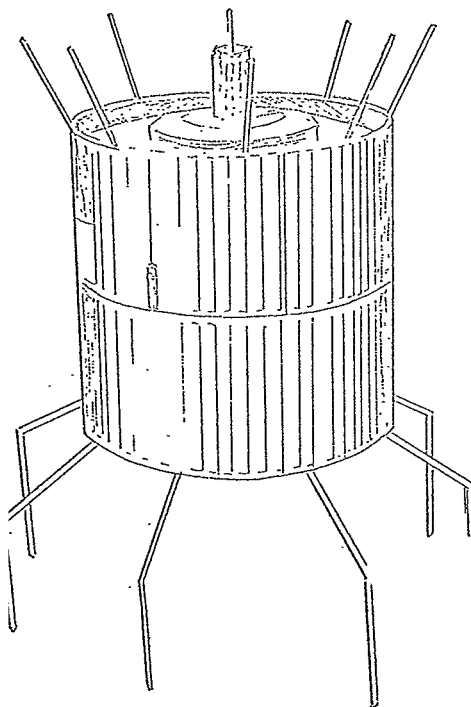


Figure 1. The ATS-1

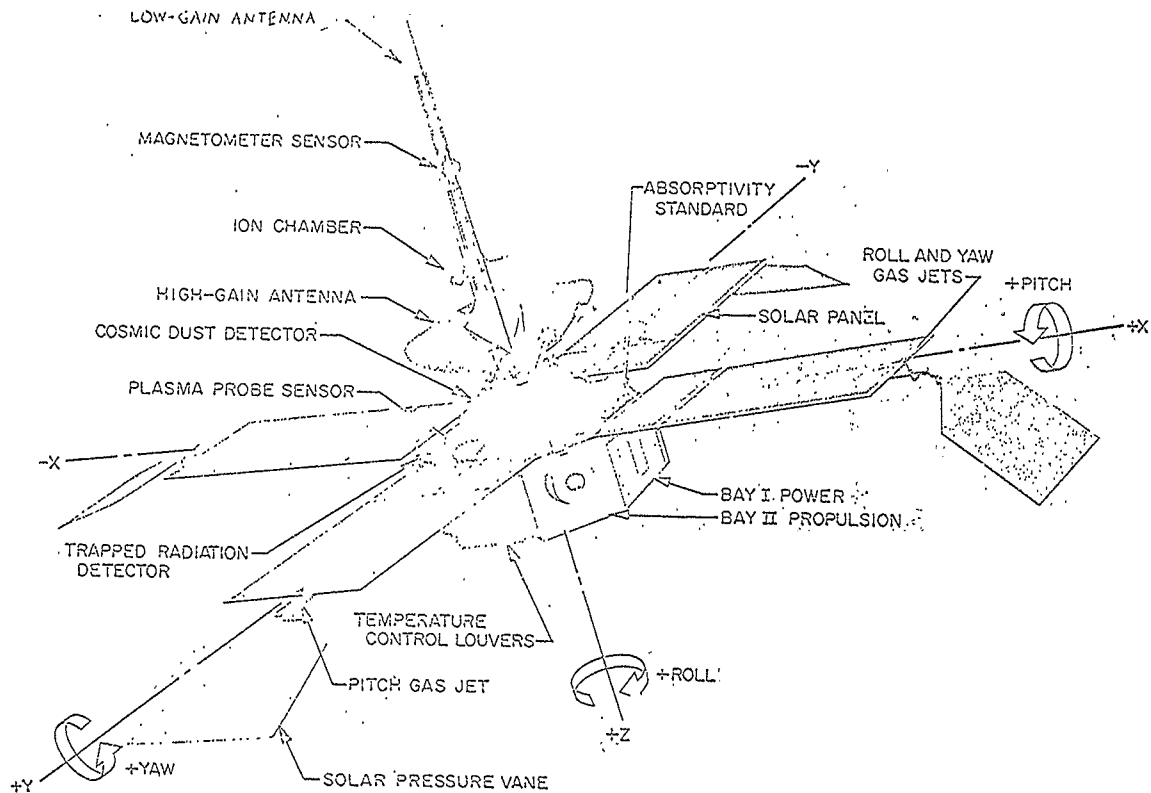


Figure 2.

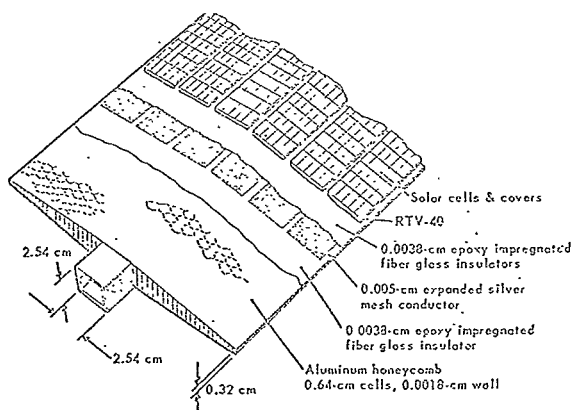


FIGURE 3. -Construction of the IMP-D solar paddles (ref. 11, copyright Aviation Week and Space Technology).

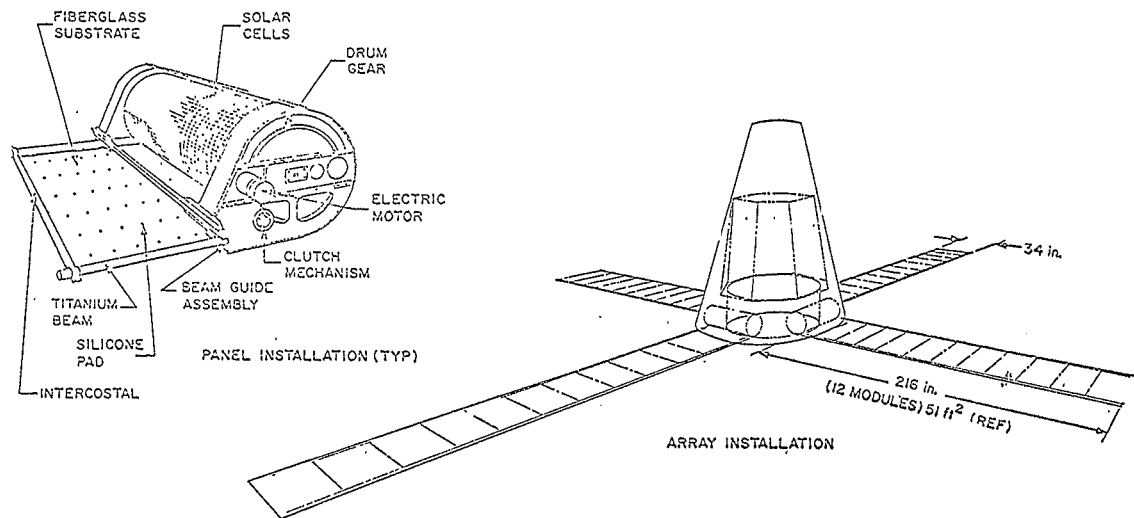


FIG. 4 DEPLOYABLE SOLAR ARRAY UTILIZING COLLAPSIBLE BEAMS

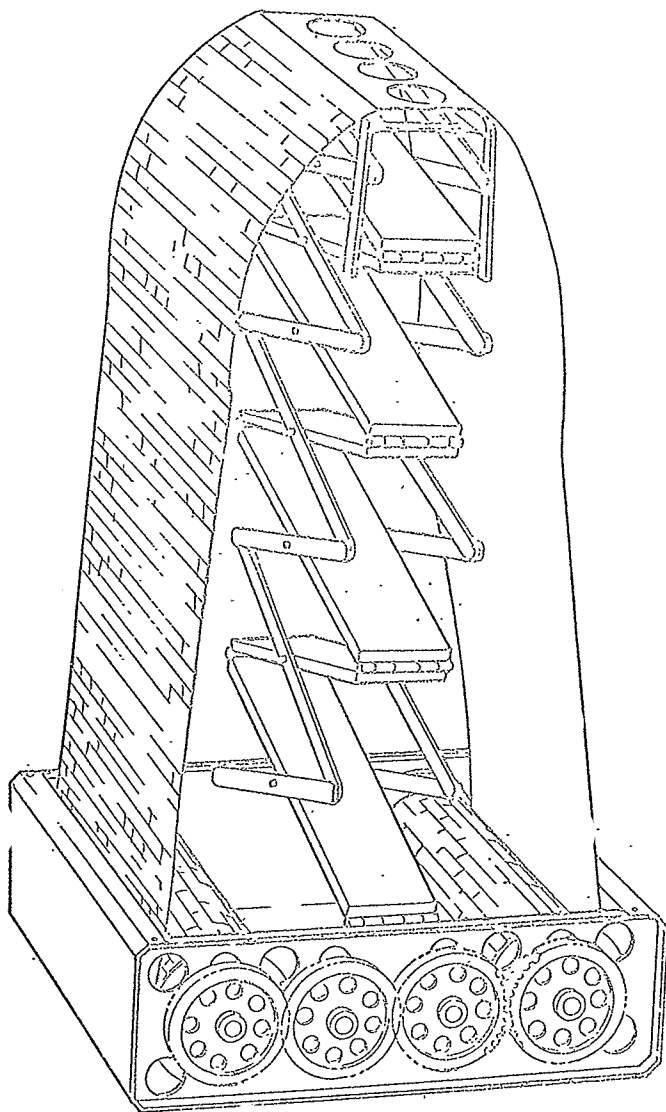


FIG. 5; ROLL-UP SOLAR ARRAY UTILIZING NEGATOR SPRINGS
AS DEPLOYING MECHANISM

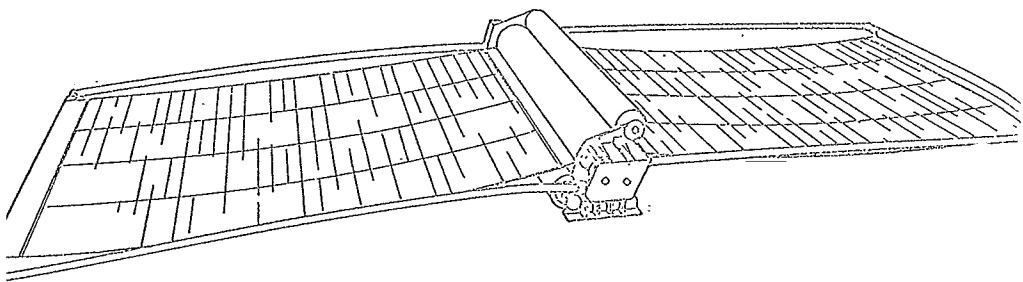


FIG. 4. ROLL-UP SOLAR ARRAY UTILIZING De HAVILLAND STEM TUBES
AS THE DEPLOYABLE MECHANISM

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SECTION: Solar Cell Array Construction

SUBSECTION: _____

TOPIC: Interconnections

THESIS (what point are we making):

The type and methods of interconnections is important to the reliability of the panels

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Types of interconnections (Figure 1)
2. Effects of temperature.
3. Effects of humidity
4. Methods of connection (series-parrallel) (Figure 2)

SOURCES OF INFORMATION:

Luft and Maiden --4IECEC
Corliss: Scientific Satellites

TO BE PREPARED BY: _____

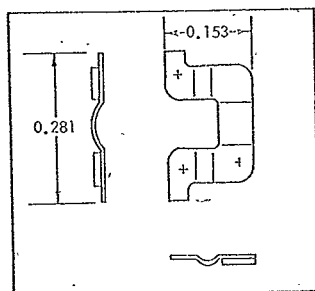


Figure 1. Interconnector with Stress Relief Loops

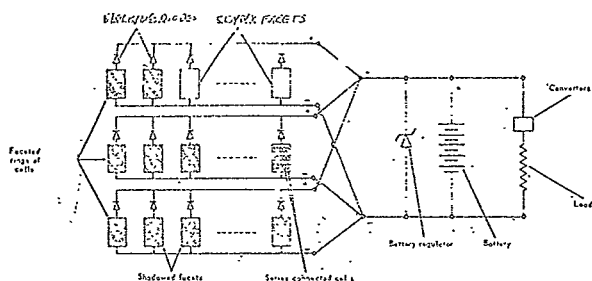


FIGURE 2 - Generalized schematic of a solar-cell power supply. Several satellite faces (or facets) are shown, but only a few are sunlit. Regulator protects battery from overcharging. (Adapted from ref. 7.)

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SECTION: Testing

SUBSECTION: _____

TOPIC: Qualification Test

THESIS (what point are we making):

Solar cell arrays are qualified for a particular spacecraft or mission through a series of tests.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Qualification testing includes imposing on the array severe test conditions - In some cases test-to-failure is required.
- 2.
- 3.
- 4.

SOURCES OF INFORMATION:

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SECTION: Testing SUBSECTION _____

TOPIC: (Mechanical Testing) Acceptance Test

THESIS (what point are we making):

Array components are subjected to acceptance testing

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. Acceptance testing involves flight qualified components being subjected to conditions which will demonstrate flight readiness and acceptability of actual mission hardware.
- 2.
- 3.
- 4.

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SECTION: Assessment of Decision Objectives SUBSECTION

TOPIC: Definitions of Power Requirements

THESIS (what point are we making): A conservative estimate of the electrical power needs of the spacecraft is a prerequisite to the initial efforts of the design group responsible for the solar cell array.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. Mission duration and rms power requirements.
2. Peak power demand
3. Requirements for output voltage and load impedances
- 4.

SOURCES OF INFORMATION:

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SECTION: Assessment of Design Objectives SUBSECTION _____

TOPIC: Launch Factors

THESIS (what point are we making): The level of vibration and acoustic noise that the solar cell array must sustain depends on the type of launch vehicle.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. Solar cell arrays should be properly tested to meet the launch environment.

2.

3.

4.

SOURCES OF INFORMATION:

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APPLICABLE TO: ☐ INTRODUCTION ☐ STATE OF THE ART ☒ CRITERIA ☐ RECOMMENDED PRACTICE ☐ APPENDIX

SECTION: _____ SUBSECTION: _____

TOPIC: Mission Environment Constraints

THESIS (what point are we making): Final design of solar cell arrays should provide for satisfactory performance in this mission environment.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. Important considerations in solar cell design are:

- . orbital parameters
- . spacecraft orientation
- . eclipse duration & frequency
- . mission life

3.

4.

SOURCES OF INFORMATION:

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SECTION: Design Considerations SUBSECTION _____

TOPIC: Solar Cell Properties and Array Construction

THESIS (what point are we making): A number of factors affecting solar cell array performance should be accounted for in the early stages of design

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. angle of illumination
temperature
load
circuit
2. design
adhesives
coverslides
substrates
- 3.
- 4.

SOURCES OF INFORMATION:

TO BE PREPARED BY:

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SECTION: Spacecraft Design Constraints

SUBSECTION _____

TOPIC: _____

THESIS (what point are we making): Spacecraft design constraints affecting solar cell array design should be afforded special consideration.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. Spacecraft constraints include:

Total Mass

Configuration

2. Attitude Control

Systems interface problems such as magnetic cleanliness and EMI

3.

4.

SOURCES OF INFORMATION:

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SECTION: Assessment of Design Objectives SUBSECTION _____

TOPIC: Spacecraft Design Constraints

THESIS (what point are we making): Spacecraft design constraints should be included from the start in the design of solar cell arrays.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. These constraints often determine the basic configuration of the array: for spin stabilized spacecraft lateral surfaces may not be sufficient for the power requirements; paddle arrays are recommended for this particular case.
- 2.
- 3.
- 4.

SOURCES OF INFORMATION:

TO BE PREPARED BY:

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SECTION: Design Objectives SUBSECTION: _____

TOPIC: Power Requirements - Load

THESIS (what point are we making): Design should be based on end-of-life power.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

SKETCH REQUIRED FIGURES OR TABLES:

1. Solar cell arrays should be sized to permit a 10% increase in power needs since load growth of this magnitude is not uncommon.
2. Operating voltage should be designed at the point of maximum power of the degraded cell under the worst temperature conditions.
- 3.
- 4.

SOURCES OF INFORMATION:

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SECTION: Assessment of Design Objectives SUBSECTION _____

TOPIC: Trajectory or Orbit Characteristics

THESIS (what point are we making): The trajectory of a deep space probe and the orbit of a satellite provide information on the illumination intensity and the exposure to radiation.

OUTLINE OF REQUIRED TEXT (to develop and substantiate thesis):

-SKETCH REQUIRED FIGURES OR TABLES:

1. Duration and frequency of eclipses should be ascertained from orbit parameters - In low orbits the spacecraft may be in eclipse 50% of the time, and the solar cell array will have to send over half its output during the rest of the time into batteries to supply power during eclipse
- 2.
- 3.
- 4.

SOURCES OF INFORMATION:

TO BE PREPARED BY:

